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Recoil Considerations for Shoulder-Fired Weapons

by Bruce P. Burns

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14. ABSTRACT
This report reviews the physics of recoil impulse and kinetic energy and the means to alter either the magnitude of these dynamic quantities or the temporal distribution of resulting interaction forces by purposeful or serendipitous mechanical filtering. Emphasis is placed on understanding the problem and the experimental approach needed to put recoil/shoulder interactions on a firm scientific basis.

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The author conducted this study when it became apparent that the problem of recoil and recoil management for individual Soldiers was fairly widely misunderstood. It is hoped that this report will serve as a primer in this area. The author thanks Tim Brosseau not only for his discussions over the years, but also his expertise in weapon dynamics and kinematics; many systems used today would not have been readily adopted without his expertise and contributions as one of the last original engineers and technicians of the old Weapons Dynamics Branch of the U.S. Army Research Laboratory (ARL) (formerly, the U.S. Army Ballistics Research Laboratory). Thanks are also due to Zac Wingard, who conducted a comprehensive technical review of this report.

This report is also intended to be used as an adjunct to ARL-SR-168[1] and in a manner such as ARL-CR-633.[2] Both this report and ARL-CR-633 include detailed information amplifying topics scantly treated in the main textbook (ARL-SR-168), and both could serve as chapters in a future updated version of the textbook.

This research was supported in part by an appointment to the Knowledge Preservation Program at ARL administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and ARL.

[1] Burns, B. P. *Advanced Ballistics Science and Engineering*; ARL-SR-168; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2008.

[2] Burns, B. P. *An Introduction to Stress Wave Propagation*; ARL-CR-633; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2009.

1. Introduction

It is apparent that there is some controversy about recoil limits for shoulder-fired weapons. There is confusion over the definition of weapon impulse and apparently somewhat "blind" adherence to a free weapon, kinetic energy (KE) limit as set by the specific governing Test Operations Procedure (TOP) 3-2-504 (1977), which also imbeds crude approximations of cartridge impulse and ignores mitigating factors. The specific factors governing the ability to fire different daily schedules are cited in the TOP, without reference, and are cited in table 1, which is reproduced here from the TOP for convenience. A recent salient point in case is the study by Blankenship et al. (2004), which was somewhat confounded by the interpretation of this TOP controlling firing safety of a hand- or shoulder-fired weapon in a testing environment. The TOP should not be interpreted as the means to define acceptable limits for Soldiers in combat, especially for specialized weapons requiring specialized training. Work by NAVSEA (Armstrong, 2009) also underscores the need for improved, sensible approaches to set limits for shoulder-fired weapons. The author's own experience found a small percentage of soldiers unable to even handle the modest levels of recoil energy associated with the M1 rifle (with 0.30-06 cartridge, ~12 ft-lb), as evidenced by massive shoulder bruising and cheek bruising. Bruising has always been associated with inadequate training to fire the weapons; however, today, there are new circumstances with a military force composed of a wider distribution of the civilian population that could be engaged in a firefight. It is also clear that there are limits to impulse (or weapon recoil energy) related to the gross motion that a firer must undergo to transmit the impulse to the ground.

Table 1. Recoil limitations set by TOP 3-2-504 for shoulder-fired weapons.

Computed Recoil Energy (ft-lb [J])	**Limitation on Rounds Fired**
Less than 15 ft-lb (20.3)	Unlimited firing
15 to 30 ft-lb (20.3 to 40.7)	200 rounds/day/man
30 ft-lb to 45 ft-lb (40.7 to 61.0)	100 rounds/day/man
45 to 60 ft-lb (61.0 to 81.4)	25 rounds/day/man
Greater than 60 ft-lb (84.1)	No shoulder firing permitted

It is very obvious that a simple measure such as the overall free impulse or KE of a weapon has limited bearing to the ability to shoulder-fire a weapon. The principal factor must be the *distribution of the impulse or kinetic energy* ***with time***, taking into account the integrated response of the weapon *and* the shooter. It does make sense to infer that net impulse or free weapon KE could apply to a *unique class* of weapon, such as a bolt action rifle with a wooden stock and a steel butt plate, but the introduction of features as innocuous as autoloading should modify those limits. Here, we will discuss the underlying physics to set the stage for a

redefinition of realistic limits for the integration of shoulder-fired weapons and the human, to include a process to evaluate limitations of shoulder-fired weapons in a scientific approach.

2. Cartridge Impulse

The first issue is to understand the physics involved in estimating firing impulse and how it is estimated. The impulse caused by the departure of the projectile is reasonably straightforward—it is the momentum of the projectile at shot exit. No one can argue about using the typically cited value of "muzzle velocity," which is usually measured some distance from the muzzle of the weapon and after it has been further accelerated by the expanding propellant gas bubble while the projectile is immersed in the bubble. It could be argued that the differences are small enough to be ignored; nevertheless, care needs to be taken about how to estimate the contribution of the gas generated by the combustion of the propelling charge. In reality, the impulse (momentum change) applied to a weapon is defined by

$$I = \sum \int F_i(t)dt;\ i = 1 \ldots n, \tag{1}$$

where $F_i(t)$ are the forces applied to the weapon as a function of time and the integration with time is over the time of application of each force. It is generally assumed that there is next to no contribution by a firing individual to the forces until after those caused by ballistic and kinematic functioning of the weapon; so net firing impulse is usually and best defined by firing the weapon using a ballistic pendulum to ascertain the net impulse of the weapon.

Presuming that all the propellant has been consumed, the momentum of the propellant gas has been studied theoretically by ballisticians for a long time. It is clear that the velocity distribution of the propellant gases when the projectile emerges is between zero at the breech of the weapon and equal to the velocity of the projectile just behind the projectile. So the propellant mass is distributed along the length of the barrel with a monotonically increasing velocity from breech to muzzle, estimated by Corner (1950) to have a momentum of approximately* half the product of the propelling charge weight and the muzzle velocity, yielding that

$$I_{se} = (M_p + C/2)V_p, \tag{2}$$

where I_{se} is the total momentum of the cartridge and the impulse transmitted to the weapon right at the time of shot emergence of the projectile from the barrel, M_p is the mass of the projectile, C is the propelling charge weight, and V_p is the muzzle velocity of the projectile. I_{se} must also be defined by

$$Ise = \int A_b P(t)dt \tag{3}$$

*Assuming that all the propellant has been converted to gas and that at least a linear distribution along the barrel of propellant gas velocity times its localized density exists.

for the case where bore/projectile friction, solid-phase propellant interaction with the chambrage cone and the propelling charge gas-phase pressure gradient effects are negligible, where P(t) is the breech pressure as a function of time, and A_b is the bore area. This demonstrates that a breech pressure measurement can be employed to estimate the impulse, at least up to the time of shot exit. Clearly, there is additional momentum incurred as the propellant gasses exit the gun barrel after shot exit, which is evident from pressure measurements made during the blown-down phase of a firing. These contributions are very complicated to estimate, but an approximation is given by Corner based on the work of Rateau (1932) and is defined by the expression

$$I_{ase} = 1.35\ C\ (RT_e)^{1/2}\ [1 + C\ /\ (12M_p)] \quad \text{for the case of } \gamma = 1.25, \tag{4}$$

where I_{ase} is the added impulse after shot exit, T_e is the exit temperature of the propellant gas, γ is an assumed value for the polytropic constant for a propellant (which varies from one propellant type to another), and R is the universal gas constant (with a host of assumptions being made). This implies the detailed knowledge of flow characteristics and the thermodynamics of the particular propellant used. Further, the interaction of the blast field on the muzzle face may serve to alter impulse a little bit. However, if a muzzle brake is used, then a great reduction in weapon impulse can be made. Of course, these details are complicated and depend heavily not only on the flow characteristics, but also the design of the muzzle brake. The area of muzzle brake design and interactions has been summarized in detail by Schmidt (1973). The muzzle brake can be used to great advantage; in fact, both Corner (1950) and Schmidt describe how a high- efficiency muzzle brake can actually cause a gun to recoil in a forward direction if the propelling charge to projectile mass ration is sufficiently large ($C/M_p >> 1$). This also results in a gun consuming a lot of propellant but achieving a muzzle velocity much greater than conventional weapon performance. But the effectiveness of a muzzle brake in a conventional weapon is very important and difficult to estimate without detailed knowledge of the brake and cartridge design and the resulting muzzle flow of the gasses once the projectile has exited the weapon. It is important to recognize that the actual impulse of a weapon firing a single shot and the free recoil energy of the weapon strongly depend on all these factors and that it is very hard to accurately establish all these figures theoretically.

Of course, there are ways to avoid launch impulse altogether. In the case of the Davis gun (Hogg, 1970), two identical projectiles are fired using a common chamber, while recoilless rifles traditionally use a lot of propellant to cause sufficient rearward metered flow of propellant gases to offset the momentum of the projectile. Finally, countermass guns are generally a combination of the two approaches, with a frangible mass being expelled rearward, along with some propellant gas to compensate for the forward momentum of the launch. Although recoilless rifles were once a major weapon for infantry antitank defense in the U.S. Army, they have all but completely disappeared due to the large signature they pose during firing. All of these approaches use more propellant than would be necessary for a conventional gun that achieves the same projectile momentum. There are otherwise no serious ballistic issues associated with size

or range. An 8-in countermass gun launching a KE projectile at 1800 m/s was demonstrated at the International Symposium on Ballistics held in Sweden in 1993. The signature, however, was massive. Recently, the Raven concept (Kathe and Dillon, 2002) has been championed by investigators at the U.S. Army Armament Research, Development, and Engineering Center's site (Benet Weapons Laboratory) located at Watervliet Arsenal, NY. Here, the propellant gases start to be released when the projectile is far enough down-bore to be unaffected by events at the breech of the weapon. This allows some of the impulse to be recovered but still causes a danger zone behind the weapon accompanied by an enhanced signature; at least no additional propellant is required compared to a conventional gun.

Some examples of these characteristics and different estimates for impulse are given in tables 2–4. Table 2 cites weapon characteristics and the sources for these data, while table 3 provides nonconservative estimates of impulse and free weapon recoil KE based on projectile impulse alone. The table also cites weapon features that significantly impact the calculation of weapon impulse and free energy and the inherent mechanical filters that affect the temporal force distribution on a firer. These latter factors will be discussed in detail in the next section.

Table 2. Ballistic properties of selected shoulder-fired weapons and cartridges.

Nomenclature	**Caliber**	**Bullet Weight**	**Muzzle Velocity**	**Weapon Weight (Empty)**	**Bullet Impulse (lb-s)**	**Source**
1853 Enfield percussion cap	0.58 in	530 gr	900 ft/s	9.5 lb	2.12	Enfield (2011)
Brown Bess	0.75 in	545 gr	1000 ft/s	9.75 lb	2.42	Bess (2011)
Springfield 30-06 rifle	0.30 in	174 gr (ball, M1)	2640 ft/s	8.67 lb	2.04	30–06 (2011)
Mauser 7.92 × 57 mm	7.92 mm	196 gr	2600 ft/s	9.0 lb	2.26	Mauser (2011)
M16A2	5.56 mm	62 gr	3110 ft/s	7.18 lb	0.86	M16A2 (2011)
M79 grenade launcher	40 mm	Approx. 200 g	247 ft/s	6.45 lb	3.38	Inetres (2011)
M82	0.50 in	46 g	856 m/s	31 lb	8.83	Burns (2012)
Boys	0.55 in	60 g	747 m/s	35 lb	9.44	Burns (2012)
PTRD PTRS	14.5 mm	64.4 g	1000 m/s	38.1 lb	14.4	Burns (2012)
Solothurn	20 mm	147 g	795 m/s	109 lb	26.2	Burns (2012)
Steyr	15.2 mm	35 g	1450 m/s	39.6 lb	11.4	Burns (2012)
Type 97 (Japanese)	20 mm	162 g	790 m/s	130 lb	28.7	Burns (2012)
12HB00 (Remington) shotgun	0.727 in	807 gr (12 × 00)	1225 ft/s	7.0 lb	4.37	Remington (2011)
Remington Express 12B0 shotgun	0.727 in	580 gr (12 × 0)	1275 ft/s	7.0 lb	3.28	Remington

Table 3. Recoil-related characteristics of selected shoulder-fired weapons cited in table 1.

Nomenclature	**Caliber**	**Weapon Weight (Empty) (lb)**	**Bullet Impulse (lb-s)**	**Weapon Recoil Velocity (ft/s)**	**Weapon KE (ft-lb)**	**Impulse Mitigation Means**	**Mechanical Filters Incorporated**
1853 Enfield percussion cap	0.58 in	9.5	2.12	7.19	7.62	None	None
Brown Bess	0.75 in	9.75	2.42	7.99	9.67	None	None
Springfield 30-06 rifle	0.30 in	8.67	2.04	7.57	7.71	None	None
Mauser 7.92 × 57 mm	7.92 mm	9.0	2.26	8.09	9.15	None	None
M16A2	5.56 mm	7.18	0.86	3.86	1.66	None	Autoloading and polymer stock
M79 grenade launcher	40 mm	6.45	3.38	16.9	28.6	None	Padded butt plate
M82	0.50 in	31	8.83	9.17	40.5	Muzzle brake	Autoloading
Boys	0.55 in	35	9.44	8.68	40.9	Muzzle brake	Padded butt plate
PTRD PTRS	14.5 mm	38.1	14.4	12.2	88.1	Muzzle brake[a]	Ad hoc butt pad used by some
Solothurn	20 mm	109	26.2	7.74	101.4	Muzzle brake	Autoloading and padded butt
Steyr	15.2 mm	39.6	11.4	9.27	52.8	Muzzle brake	Autoloading with long-stroke recoil mechanism
Type 97 (Japanese)	20 mm	130	28.7	7.11	102.0	Muzzle brake	autoloading (details sketchy)
Remington 12HB00 shotgun	0.727 in	7.0 (typical)	4.37	20.1	43.9	None	Padded butt plate and padded jacket common
Remington Express 12B0 shotgun	0.727 in	7.0 (typical)	3.28	15.1	24.8	None	Padded butt plate and padded jacket common

[a]Armstrong (2009) contends that this Soviet single-shot, manually-operated, rotating bolt weapon actually has a recoil mechanism—a feature unconfirmed by any other available source. Some photographic evidence and online articles exist that demonstrate the widespread usage of this weapon and its more advanced semiautomatic cousin, the PTRS rifle, including at least one photo of an individual modification to the PTRD rifle showing cloth attached to the butt of the weapon. The latter was obviously implemented to lessen the recoil load and damage to the individual's shoulder. It should also be noted that the German Wehrmacht and Luftwaffe of World War II (WWII) considered the recoil of the Solothurn rifle to be too excessive to allow general production and issue of the rifle; this was clearly not the case with the Soviet rifles.

Table 4. A comparison of impulse estimated four different ways: the projectile alone, impulse at shot exit as estimated from Corner (1950), as defined (inferred from the free recoil KE) by TOP 3-2-504 (1977), and as estimated by Armstrong (2009).

Nomenclature	Caliber	Weapon Weight (Empty) (lb)	Bullet Impulse (lb-s)	Propelling Charge Weight (gr)	Cartridge Impulse at Shot Exit [b] (lb-s)	Impulse Inferred From TOP 3-2-504 (lb-s)	Recoil Impulse From Crane (lb-s)
1853 Enfield percussion cap	0.58 in	9.5	2.12	68	2.26	2.60	NA
Brown Bess	0.75 in	9.75	2.42	100	2.64	3.20	NA
Springfield 30-06 rifle	0.30 in	8.67	2.04	≈48[a]	2.32	3.02	2.6[c]
Mauser 7.92 × 57 mm	7.92 mm	9.0	2.26	47	2.53	3.21	NA
M16A2	5.56 mm	7.18	0.86	26[a]	1.04	1.49	1.34
M82	0.50 in	31	8.83	235[a]	10.3	14.0	11.92
Boys	0.55 in	35	9.44	225[a]	10.7	13.7	11.98
PTRD PTRS	14.5 mm	38.1	14.4	470[a]	17.8	26.4	23.42
Solothurn	20 mm	109	26.2	570[a]	29.5	37.7	36.75
Steyr	15.2 mm	39.6	11.4	393 (estimated)	16.6	29.6	NA
Remington Express 12B0 shotgun	0.727 in	7.0 (typical)	3.28	≈27[a]	3.36	3.55	3.53

[a]Cited or inferred from Armstrong.
[b]Based on methodology in Corner.
[c]Value for similar M14 rifle firing standard North Atlantic Treaty Organization 7.62-mm cartridge (Armstrong, 2009).
Note: NA = not available.

Table 4 presents individual cartridge data based on the estimated propelling charge weight to derive the impulse at projectile exit from the muzzle, the total impulse inferred from TOP 3-2-504, and the total impulse from Armstrong (2009). The latter two approaches use a calibrated factor to describe the contribution of the propelling charge gases as characterized by propellant weight and the muzzle velocity of the weapon. The expression used is

$$E_r = M_g[(kC + M_p)\, V_p/M_g]^2, \tag{5}$$

where E_r is the recoil energy, M_g is the mass of the weapon, and k is a fudge factor taken to be 1.75 in the TOP and 1.35 by Armstrong (based on experience, including pendulum firings of certain weapons). The net impulse must then be

$$I_t = (kC + M_p)\, V_p. \tag{6}$$

In the case of very large values of C compared to M_p, which must imply a very high muzzle velocity weapon and cartridge system, and for the weapon to be able to recoil *forward* as asserted by both Corner (1950) and Schmidt (1973) for high-efficiency muzzle brakes, k must clearly be negative. So there is a lot of room for discussion about the appropriate value for k; clearly, it depends on many factors, including the weapon one is discussing, and, in particular, about the design of the muzzle brake. Figures 1 and 2 illustrate the size of some of these guns—in this case, some of the Soviet 14.5-mm antitank rifles. (Note the very large muzzle brake.)

Figure 1. A WWII Soviet antitank rifle unit (note the size of the weapons).

There is also the issue over what time period is impulse transmission a concern. Ultimately, the impulse becomes manifested in the displacement of at least a portion of the firer's body. If a limit exists, it may depend on whether it results from one shot or repeated, high-frequency shots. An interesting case is posed by shoulder-firing of automatic weapons, of which the German WWII MG42 represents an extreme case. The MG42 (Smith and Smith, 1962) averaged around 20 shots per second (the actual rate depended on the springs and ran from 18 shots per second to 25 shots per second) and had no muzzle brake; it did, however, have a flash hider. The weapon weighed 26.5 lb and fired the 7.92- × 57-mm cartridge that had a projectile impulse of 2.26 lb. This implies a weapon recoil velocity of at least 2.74 ft/s and a free weapon KE of at least

Figure 2. The Soviet gas-operated, semiautomatic 14.5-mm PTRS antitank rifle in detail.

3.1 ft-lb. A 1-s burst from this weapon delivered (our computation here ignored the contribution of the propellant to the net impulse) an impulse of more than 45.2 lb-s and had a weapon KE of more than 61.9 ft-lb. If we use the approach outlined in TOP 3-2-504, then the values for both weapon impulse and a free energy for a second-long burst become 64.2 lb-s and 125 ft-lb, respectively. This particular light machine gun was issued to each German infantry squad and, occasionally, two per squad. It was the mainstay of German infantry defensive fires. Obviously, it was not a challenge to human endurance to operate. Doubtless one had to learn how to master the recoil loads posed by the weapon, and virtually every successful German infantryman learned to do so. It is clear that the crucial issue may not be impulse or weapon KE but, instead, the *rate* at which either is absorbed by the shoulder; possibly, force acting over a certain period is a far better measure. Surely, net impulse is related to the gross motion of the firer. For certain weapons, a separate practical limit might be set by this consideration, but the limit might be also dependent of the firer's position (prone vs. offhand, et al.). The second point is that our troops no longer have a personal rifle or carbine that can readily injure a shoulder or cheek if fired improperly. To be successful with any of the weapons listed, except possibly for the M16 rifle firing standard ammunition, a firer can suffer damage if he/she is not "one with the weapon." The weapon must be held firmly to the shoulder and with the cheek "spot-welded" to the thumb holding the stock (for rifles). Otherwise, a short period of free weapon recoil followed by impact

to either the cheek or shoulder will usually prove to be damaging.* The more one becomes "gun-shy," the worse things become. The same goes for other classes of weapons, including the gunner's role in a M551 Sheridan vehicle, where the recoil impulse is sufficient to lift the front road wheels a substantial distance off the ground. The gunner must be "one with the vehicle" to avoid being slammed in the head by the brow pad. By pressing one's forehead against the brow pad, injury is prevented.

3. Impulse Management

The impulse due to firing at a constant temperature is invariant given a cartridge and a defined weapon. The surest way to ascertain the value of the impulse is via ballistic pendulum tests. These tests will reveal the total impulse but not the *rate* at which impulse is generated (actually, the force as a function of time). In the case of a muzzle loader or hand-operated, bolt-action weapon, the impulse is delivered over a short time, on the order of a few factors times the time it takes the bullet to transit the bore of the weapon; this is, perhaps, subtly modified by the stock of the weapon and the material used to construct the stock (e.g., polymers are notoriously rate-sensitive materials). Everything changes when semiautomatic (one shot per pull of the trigger), automatic (continuous fire at a cyclic rate until the trigger is released or the weapon expends its ammunition), or recoil mechanisms are introduced. In the case of a gas-operated weapon, the bolt is unlocked when the bullet is close to reaching the muzzle, and the bolt is thrust rearward by the propellant gases against the action of a spring. The impulse generated *before* the bolt is unlocked passes through the bolt to the receiver and stock of the weapon. Some, if not all of the impulse generated *after* the bolt starts its rearward motion goes into the bolt and gets transmitted to the receiver and stock at a more leisurely pace. As a result, the impulse is spread over a longer time, and the average force associated with the impulse is reduced. Further, in some weapons, a buffer (spring/damper element) is put in series with the bolt spring to smooth out the impulse delivery. In a blow-back automatic weapon (the bolt is not locked, but reacts inertially against a spring caused by the pressure at the base of the cartridge case), virtually all the projectile momentum and much of the propellant gas momentum is transmitted to the motion of the bolt, dramatically altering the rate at which impulse is transmitted to the receiver and stock of the weapon. In the case of a recoil operated weapon, like most heavy machine guns and the Steyr antimateriel rifle (AMR), the barrel and bolt undergo a recoil stroke (in the case of the Steyr weapon, around 8 in), causing a huge temporal dispersion of the cartridge impulse. In the case of the Steyr weapon, the cartridge impulse is also considerably reduced by the muzzle brake.

*The author recalls the variability in tissue damage caused by the M1 rifle as used in basic training and qualification (during my time excess "black tips" … armor-piercing ammo … was used up). Besides the "M1 thumb," signatures of inept interaction included a visibly-bruised cheek and black eye and shoulder bruises, including massive ones extending six or more inches in span. The flame thrower was always given to an athletic, big guy, and firing the rifle grenade from the shoulder was a "manly" thing to do. Some of us actually did it.

In the latter case, the length of the recoil stroke and the mass of the recoiling parts are huge factors. They are related to the *average* recoil force through the approximate equation

$$I^2 = 2\,k\,(M_r \times L_r \times F'_r), \tag{7}$$

where I is the net delivered impulse (after taking a muzzle brake into account), M_r is the mass of the recoiling parts, L_r is the recoil stroke, and F'_r is the *average* recoil force defined by

$$F'_r = [\int F_r(\tau)d\,\tau]/t \text{ , with } 0 \le \tau \le t, \tag{8}$$

with t being the time over which the impulse is transferred. The quantity k is a factor to make the units, etc., work out. Note that the net impulse needs to be well-defined to design the recoil mechanism. Since the average recoil force is spread out over a much longer time compared to the characteristic interior ballistic time, it is much lower than would be deduced from the force levels defined by the pressure-time curve of the cartridge. Further and just like a large-caliber weapon mounted in a tracked vehicle or attached to the ground, the firing person acts as yet another mechanical filter to further reduce the peak force and spread the impulse out further in time,[*] and the firer will react to the impulse as dictated by the equation just cited. Given the mass of a person (or the mass of that part of the person that moves, which is different for different firing positions) and a limitation set for the magnitude of force, the resulting motion of the person is simply a consequence.

We can apply this equation a couple of times to illustrate its importance. If we examine shoulder/weapon interaction, where M_r becomes the mass of the weapon, then there is a tradeoff between the average interaction force between the shoulder and the butt of the weapon and the distance the butt travels when the force is applied. Likewise, there is an interaction of the body with the ground and its resulting motion. In the prone position, a recoil load placed at the shoulder deforms the shoulder, while the body transmits the impulse to the ground via friction. If the average shear force between the body and the ground is small enough to not overcome static friction, the body will not translate. If the converse is true, then the body will slide along the ground. Firing from the offhand (standing) position is entirely different. Here, the upper part of the body can displace a lot as it rotates relative to the lower part of the body. The anticipation of the recoil forces also allows the body to prepare for the recoil motion and minimize the peak force and/or resulting gross motion of the body. Excessive anticipation, known as flinching, can, of course, result in an inaccurate shot. Of course, there are levels of impulse where excessive motion of the body cannot be prevented; although the interaction forces at the shoulder might not be damaging, the gross motion of the body might become, at least, unnerving. Perhaps, this is why it was recommended that the handling and firing of a machine gun during a close assault be conducted by holding the weapon at the hip and adjusting fire (to the desired impact point) by

[*]Incidentally, there have been large-caliber artillery systems designed so that the upper carriage within a recoiling lower carriage. Ultimately and after passing the forces through the rest of the structure, this finally transmits the ***impulse*** to the ground. It is said that the famous WWI “French 75” was specified to not cause a glass of wine placed on a wheel of the weapon to spill when the weapon was fired. The famous, and definitive, hydropneumatic recoil mechanism resulted.

observing the fall of shot, not by firing from the offhand position. Since the gross reaction of the body is dependent upon body mass (the distribution of body mass and a host of other factors), the reaction of the body and limiting impulse levels must vary from individual to individual. Where the recoil might be excessive to one individual, it might be just fine to a heavier, more experienced, and/or stronger person.

Making detailed measurements of the force, impulse, and energy associated with firing a weapon has been conducted many times over the years, especially as pioneered by the old Ballistics Research Laboratory, now most of the Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL).[*] An example of the type of work by others is shown in data presented by Armstrong (2009). In figure 3, which shows the manner in which force data was gathered, the firer (a human) can easily be in and relevant to the experiment. In fact, many subjects can be involved, extending the data set over a wide range of builds, bone density, etc., as well as a range of clothing. Perhaps the existence of pack straps might make a difference. In figure 4, the output of force measurements is shown for three weapons, two rifles for the 0.308 Winchester and 0.243 Winchester rifle cartridges and the third a Steyr 15.2-mm AMR. Note the difference in peak force (the large-caliber AMR has a peak force about equal to the 0.243 Winchester rifle cartridge, while the Winchester 0.308 cartridge caused a peak force more than twice either of the other weapons). Also note the duration of the force. If each of the force curves over the time interval were integrated, the result should be the same as that derived from a ballistic pendulum experiment for each weapon. The obvious conclusion is that the recoil mechanism designed into the Steyr AMR system made a huge difference in the force level delivered to and sensed by the human firing the weapon. It should also make a very significant difference in tissue and bone damage to the human firing the weapon.

There have also been attempts to create models of the body to predict its dynamics during firing. Hutchings and Rahe (1975) developed a simplified, analog computer model to represent the body in conducting laboratory experiments to predict motion of the body and weapon as a consequence of body motion. Particularly enlightening were some of the simulations of firing automatic weapons. Excursions in biological factors were considered, and certain sensitivity analyses were included. Any published advances in physics-based modeling of the act of firing a shoulder-fired weapon since then are not known at this time. Obviously, there should be vastly improved means at our disposal to generate a much higher fidelity model.

[*]The suite of experimental measurements possible includes not only gross measurements as cited here, but also detailed kinematics of weapon functioning to ascertain performance and trouble-shoot weapon malfunction issues. This organization designed competitive candidates for the squad automatic weapon (SAW), currently manifested as the 5.56-mm light machine gun based on a foreign design, and devised critical experiments to troubleshoot issues with virtually every automatic weapon in service with the U.S. Army and Marine Corps. Today, excellent expertise still exists in ARL, but principles that allowed success in past weapon designs by others are now being relearned by new sets of engineers (Brosseau, 2011).

Figure 3. Experimental arrangement to make force measurements during firing based on the Steyr AMR.

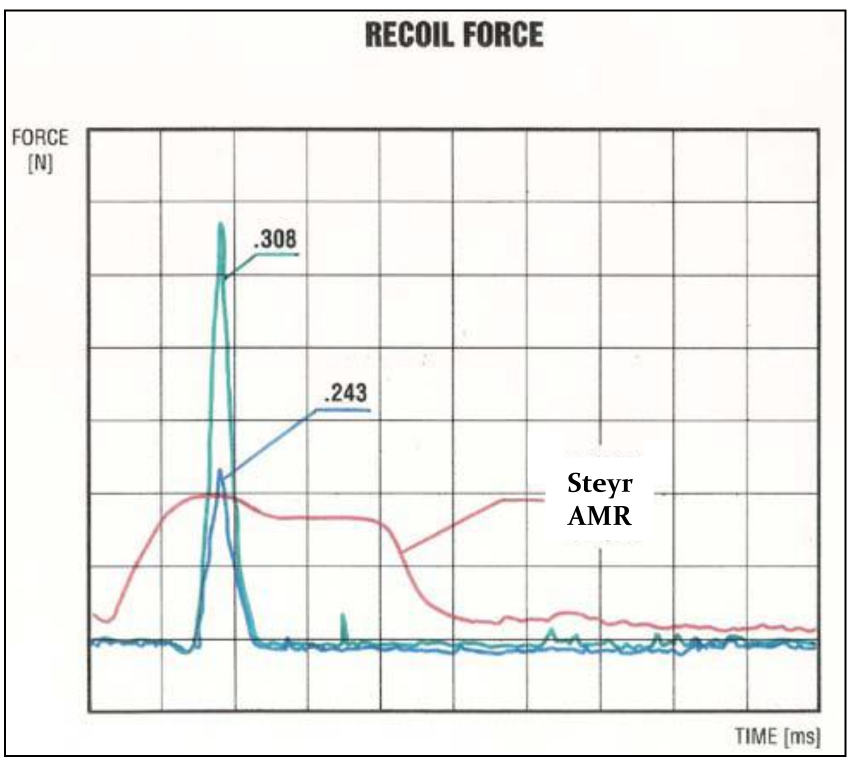

Figure 4. Force vs. time measurements for three weapons (the time of firing is not identical).

4. Conclusions

In dealing with the issues associated with the accurate firing of a rifle, light machine gun, AMR, or grenade launcher, sound physics should be applied before the deduction and enforcement of a Draconian "rule" about what is tolerable and what is not tolerable. TOP 3-2-504 states what is approximate for only certain types of weapons and must come with caveats, tacit, or otherwise. The "free impulse" or "free kinetic energy" of a weapon system are, in fact, a bit difficult to nail down. Ballistic pendulum experiments seem to be the best way to determine the total magnitudes of these quantities, but not the temporal distribution of force. Accurate force vs. measurements appear to be crucial to understanding mechanisms of the human body related to individual weapon firing loads. Thanks to the prior work of others, the way to ascertain such data has been shown in this report.

Echoing the conclusions of the study by Blankenship et al. (2004), much applied science and engineering needs to be accomplished, both experimentally and theoretically, before rational criteria for the shoulder-firing of weapons can be developed with a pedigree far better than that espoused in TOP 3-2-504. It must also be stated that the TOP is in place for the testing environment and not for Soldiers in combat, which should be the objective of a robust study. The approach taken in the study by Blankenship et al. is on the right track. However, this approach needs to have good theoretical and experimental mechanics (physics) inserted to measure force and other quantities accurately as a function of time and to create an updated model of the human integrated with a firing weapon, both in single shot mode and in the automatic mode for weapons capable of doing so. Gathering accuracy-related data is also important. Biological measurements of human reactions and strength can serve to provide needed data to such a computational model. Different firing positions and weapon types need to be included, along with female and male subjects of appropriately-varying physical composition, exercising varied firing schedules to satisfy statistical principles (developed by experimental design approaches). A certification process also needs to be developed to ensure that the firing individual really knows how to be "one with the weapon" for each weapon examined. Specialized "laboratory" weapons can be used to evaluate the effects of differing impulse levels. Accurate measurements of weapon characteristics as well as firing impulse need to be conducted. Weapons needing shooters with particular physical and mental attributes also need to be considered, e.g., snipers using high-powered rifles and/or AMRs. This program could perhaps provide data to better cull sharp-shooting weapon specialists and be a great applied research project, leading to criteria for the development of future individually-fired weapons.

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